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SCIENTIFIC POTENTIAL AND DESIGN CONSIDERATIONS FOR AN UNDULATOR BEAM LINE ON ALADDIN STORAGE RING

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I. Introduction

The unique features of undulator radiation, i.e., high photon flux and brightness, partial coherence, small beam divergence, spectral tunability, etc., mandate that undulators be included in the future plans for Aladdin. This will make it possible to perform the next generation of experiments in photon-stimulated spectroscopies. A team of scientists (see Appendix) has now been assembled to build an insertion device (ID) and the associated beam line at Aladdin.

In considering the specifications for the ID, it was assumed that the ID beam line will be an SRC user facility. Consequently, design parameters were chosen with the intent of maximizing experimental flexibility consistent with a conservative design approach. A tunable "clamshell" undulator device was chosen with a first harmonic tunable from 35 to 110 eV to operate on a 1 GeV storage ring. Higher harmonics will be utilized for experiments needing higher photon energies.

Section II contains selected examples of scientific goals that will be achievable with the device. Section III presents the insertion device design parameters. Section IV gives consideration to the beam line, including monochromator and associated optics. The members of this insertion device team (IDT) are listed in the Appendix.

In this proposal, the SRC undulator will be referred to as U1 and the insertion device team as U1-IDT. During all stages of the U1 design, the U1-IDT will consult with the accelerator team at SRC.

II. Scientific Goals

The goal of the U1-IDT is to utilize the enhanced intensity and brightness from this undulator to explore new scientific possibilities in materials, molecular, surface and photophysics research. The undulator characteristics will translate into new standards in energy, angular, and spatial resolution as outlined in a few select examples below.

Recent advances in the study of heavy fermion superconductors have focussed renewed interest in the properties of narrow-band actinide intermetallic compounds. The width of the electronic structural features of interest are expected to be significantly (~ 10 times) less than the resolution of present-day synchrotron light sources. The undulator will (i) enable the necessary resolution to be achieved and (ii) permit the selective enhancement or suppression of the important f-electron emission, by tuning the photon energy through the d-shell core levels. Thus, the proven value of photoemission studies will be extended to the elusive properties of 5f-band systems.

Conventional photoelectron measurements permit variability of an impressive array of parameters including photon energy and polarization, and emitted electron kinetic energy and ejection angle. Another fundamentally important parameter is not as accessible--the electron spin and its vector components. Spin detectors are generally based on sizable Mott scattering asymmetries, but the scattering efficiency is usually notoriously small. The cost in lost count rates is typically ~ 10^4. The enhanced flux of the undulator is necessary to open the frontier area of spin-resolved studies to routine investigation. The motivation is to (i) pursue basic questions concerning itinerant ferromagnetism, (ii) to explore the virgin field of the magnetism of epitaxial monolayers with tailored lattice constants, and other new materials with technological potential, and (iii) to permit unprecedented studies of resonant photoemission enhancement mechanisms.

Gas phase studies suffer from the inherently low density of the specimen of interest. Nevertheless, many of our general concepts in photoelectron spectroscopies derive from gas-phase, atomic and excited-atom models. The availability of the high-intensity undulator source will permit: (i) both shape resonance and autoionizing resonance mechanisms to be explored; (ii) the observation of vibrational sidebands associated with (non-resonant) core-level excitations which mark the breakdown of the single particle model; and (iii) sophisticated timing experiments to a) probe short-lived, laser-induced excited states, and b) to perform various electron-electron coincidence experiments that are presently hampered by low count rates.

The above possibilities in atomic and molecular photophysics will lead to new advances in surface science. The kinetics of desorption or reaction of state-selected species and detailed spatial mappings should be routinely possible. These studies have the additional practical advantage of being relevant to i) catalysis and microelectronics research, and ii) the vacuum design of future synchrotron light sources, such as the proposed 6-GeV machine that has captured the interest of the nation.

The above discussion gives a sampling of the broad range of scientific interests of the U1-IDT. With the new capabilities afforded by the ID, it is likely that new scientific frontiers will also be opened.

III. Undulator Design

To best satisfy the needs of the U1-IDT, the choice has been made to design a "clamshell" tunable insertion device (ID) containing rare earth-cobalt (REC), such as $SmCo_5$, permanent magnets. With this design, spectral tuning is accomplished by varying the magnet pole gap G. It is, of course, desirable to have as large a tuning range as possible consistent with the need to guarantee minimal disruption of normal machine operation. Typically this dictates undulators be designed to operate with deflection parameter $K \sim 1$. This mode also provides high intensity in the first harmonic while producing a relatively low output of radiated power at higher energies.

The peak amplitudes of the alternating magnetic fields (B) on the ID axis are a function of G/λ_0, where λ_0 is the undulator wavelength. The dependence of B on G/λ_0 varies for different materials (and even for different batches of the same material) and must be determined for a matched set of magnets. For REC materials,

$$B = A \exp(- \pi G/\lambda_0)$$

where $1.2 \lesssim A \lesssim 1.6$. The deflection parameter is given by

$$K = 0.934 \; B \; \lambda_0 .$$

Thus the maximum value of K is determined by the minimum permissible gap and by the undulator wavelength. By opening the clamshell, an arbitrarily small value of K can be obtained. However, excessively low values of K ($\lesssim 0.5$) result in low photon flux and are generally of little interest.

The energy of the photons in the first harmonic (measured on the undulator axis) is given by

$$E_p = \left(\frac{2\gamma^2 hc}{\lambda_o}\right)/(1 + K^2/2).$$

The parameter γ, proportional to the electron beam energy, as well as h and c, have their usual meanings. Thus for a given set of REC magnets, the energy of the first harmonic peak is uniquely specified by G and λ_o.

The key design considerations[1] are summarized in Fig. 1. The lower (solid) curve of Fig. 1 shows the relationship between the first harmonic peak energy and λ_o for typical REC magnets (A = 1.5) and a (closed clamshell) gap of 3.5 cm (determined by physical constraints). Along this extreme curve, which specifies minimum attainable values of E_p, the value of K varies with λ_o. The upper curve (K = 0) shows the maximum attainable values of E_p which occur at the limit of zero photon flux. Also shown in Fig. 1 are curves of constant K. Thus we see that the effective tuning range of E_p at any λ_o must fall between the upper and lower curves shown in Fig. 1 (and more realistically, between the lower curve and the K ~ 0.5 curve). The corresponding gap adjustments for the λ_o = 7 cm design are also shown.

One could choose to maximize E_p (at ~ 250 eV) by choosing a short undulator period but this choice would sacrifice all tunability and would restrict operation to a single, low K mode of operation. At the other extreme, one could select a longer undulator period, and thus obtain, at high K operation, a wider tuning range but lowering E_p. Of course, high K operation would dramatically change the nature of the spectrum. Most of the intensity would appear in high harmonics and beam divergence increases. An intermediate choice which appears to best meet projected needs fixes λ_0 at 7-7.5 cm. A 3.5 m long undulator would contain 47-50 periods. This design choice provides tunability (at 1 GeV) in the first harmonic between ~35 and 110 eV (with the lower limit depending on precise magnet properties). For this design, with the clamshell closed, K = 2-2.5. Note that if the gap could be further reduced below 3.5 cm, additional design flexibility would be available.

If the Aladdin storage ring is operated at 0.8 GeV (rather than 1.0 GeV) either for technical reasons or to meet the requirements of the other users on bending magnet beam lines, it will reduce E_p by 0.64 (and the spectral range becomes ~20 to 70 eV). Peak intensities from U1 will drop by a comparable scaling factor.

Spectral brilliance is affected by the electron beam parameters. Our best current estimates of the electron beam size and divergence parameters for Aladdin are [2]

$$\sigma_x = 0.516 \text{ mm}, \ \sigma_y = 0.365 \text{ mm}$$

$$\sigma_{x'} = 0.129 \text{ m rad}, \ \sigma_{y'} = 0.092 \text{ m rad}.$$

Using these electron beam parameters and λ_0 = 7 cm with 100 ma of beam current, the on-axis brilliance is calculated and displayed in Fig. 2. Curves are shown for minimum gap operation (3.5 cm) and for a gap of 6 cm (for these calculations, the parameter A = 1.24).[2]

For the available tuning range of the undulator considered in Fig. 2, and with 100 ma of beam current, the total radiated power will vary between approximately 3 and 30 watts. The power in the fundamental for the corresponding tuning conditions varies between ~2.7 and 12 watts. If the electron beam current is increased to 500 mA the flux plotted in Fig. 2 increases proportionately, and the total radiated power increases to 15-to-150 W range.

IV. Undulator Beam Line

The proposed undulator will have a tunable first harmonic in the 35-110 eV photon range. At minimum gap, a high photon flux will be available from higher harmonics so that the usable photon energy range can be extended to ≈500 eV. Reflection grating monochromators are best suited in this energy range. A number of factors are to be considered in the choice of a monochromator. Among these are throughput and resolution, but one should not ignore initial cost, upkeep, simplicity, power dissipation, etc. We evaluate existing and proposed monochromators below.

The Rowland circle mounting utilized in the Extended Range Grasshopper (ERG) and grasshopper monochromators yields high resolution with spherical gratings. However, the heat load (estimated at ≈ 100 watts) on the Codling mirror at the entrance slit may prove too large to prevent distortion. Moreover the narrow undulator beam would require large radii of curvature to properly illuminate the grating. In addition, the four optical elements (including a re-focusing mirror) result in unnecessary loss of flux.

Cost is a major consideration with the toroidal grating monochromator (TGM), especially when one takes into account the periodic replacement of gratings which will become carbonized in the high undulator flux. It would be preferable to retain simple and rugged construction of optical elements which may require some form of cooling.

The recent design of an undulator monochromator (dubbed the UMO) by Brown and Hulbert[3] offers the best characteristics for our application. It is a variation of the recently refined plane grating monochromator now in use in Berlin. The UMO retains the relatively simple, compact and rugged mechanical design of the highly successful Grasshopper. It consists of three optical elements, (Fig. 3) the first two of which are a plane movable mirror and a plane rotatable grating. The first mirror can be made of silicon carbide so that it could handle the heat load without distortion. Cooling could be added if found necessary. The final mirror is an ellipsoidal focussing mirror which receives only a small heat load. A simple re-programming of the drive motors allows the user to operate either in the high-resolution "virtual mode", or the high throughput "constant blaze" mode. In "virtual mode" operation a large image reduction occurs at the focus of the elliposidal focussing mirror. The resulting small spot size will be useful in spatial resolution studies. This, combined with the high efficiency, yields a highly versatile apparatus. The plane grating should be substantially cheaper than either toroidal or spherical gratings which will facilitate periodic grating replacement.

The UMO resolution will depend on the source size. In the "virtual source" mode this will probably equal or even exceed the ERG resolution for gratings with equal D-spacing. It can be shown that

$$\Delta E = E^{3/2}\ \Delta\xi/99.5\ [D(C^2 - 1)]^{1/2}$$

where $\Delta\xi$ is the angular subtence of the source, D is the grating spacing, and C is a constant that relates the incident and exit angles. Using a C of 2.25, as suggested by Brown & Hulbert, a grating of 1200 lines/mm and a $\Delta\xi$ determined from the size and angular divergences of the electron beam in the undulator, i.e. σ_y = 0.365 mm and $\sigma_{y'}$ = 0.092 mrad, and a distance of 15 m from the source, one obtains $\Delta E \approx 35$ meV at 100 eV photon energy.

A variable aperture cooled slit will be designed which will enable the user to utilize the highly structured nature of the undulator photon beam. By placing it near the undulator it may be possible to further increase the resolution. A special crescent shaped exit slit will be designed to conform to the shape of the exit photon beam as obtained from ray tracing. The mirror and gratings (possibly SiC) will be of non-standard design (thickness > width) to allow maximum dissipation of heat with minimum distortion. The remaining portions of the beam line will utilize standard elements (beam detectors, pumps, etc.). We have the great advantage of having one of the originators of the UMO concept on U1-IDT.

REFERENCES

1. B. Veal, Light Source Document, Argonne National Lab (in preparation).

2. S. Kim, Light Source Document LS-16, Argonne National Lab, March 20, 1985.

3. F. C. Brown and S. L. Hubert, Nucl. Instrum. Methods 222, 42 (1984).

FIGURE CAPTIONS

Fig. 1: The dependence of the photon energy from U1 as a function of undulator gap G and wavelength λ_0 (Ref. 1).

Fig. 2: Spectral brilliance from U1 as a function of energy using the Aladdin source parameters given in the text (Ref. 2).

Fig. 3: Schematic diagram of the UMO concept showing two translated positions of the scanning SiC mirror.

APPENDIX

U1-IDT Composition

Spokesperson: G. K. Shenoy, Argonne National Laboratory

Members

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2.	S. D. Bader	Argonne National Laboratory
3.	J. L. Dehmer	Argonne National Laboratory
4.	S. H. Kim	Argonne National Laboratory
5.	G. S. Knapp	Argonne National Laboratory
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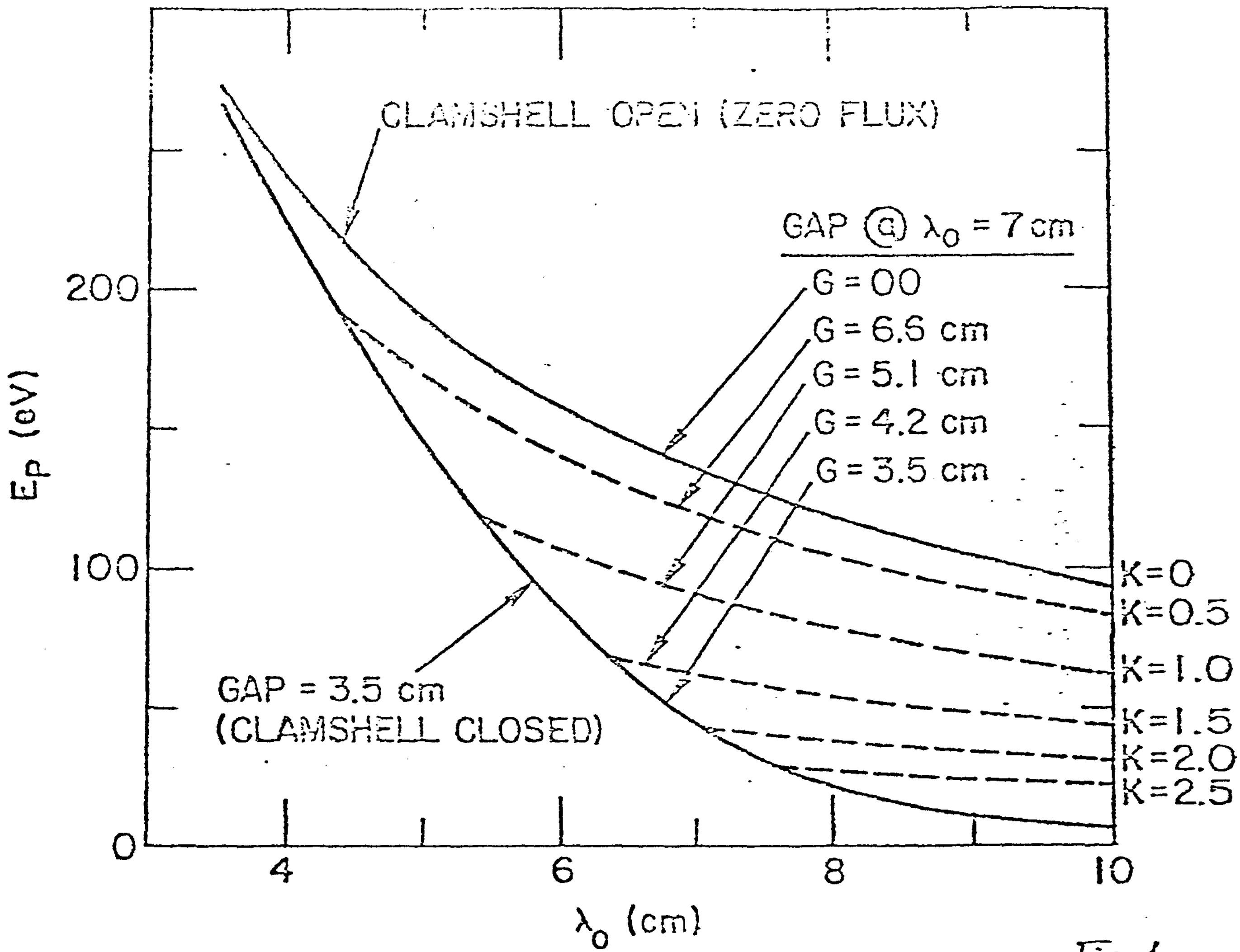
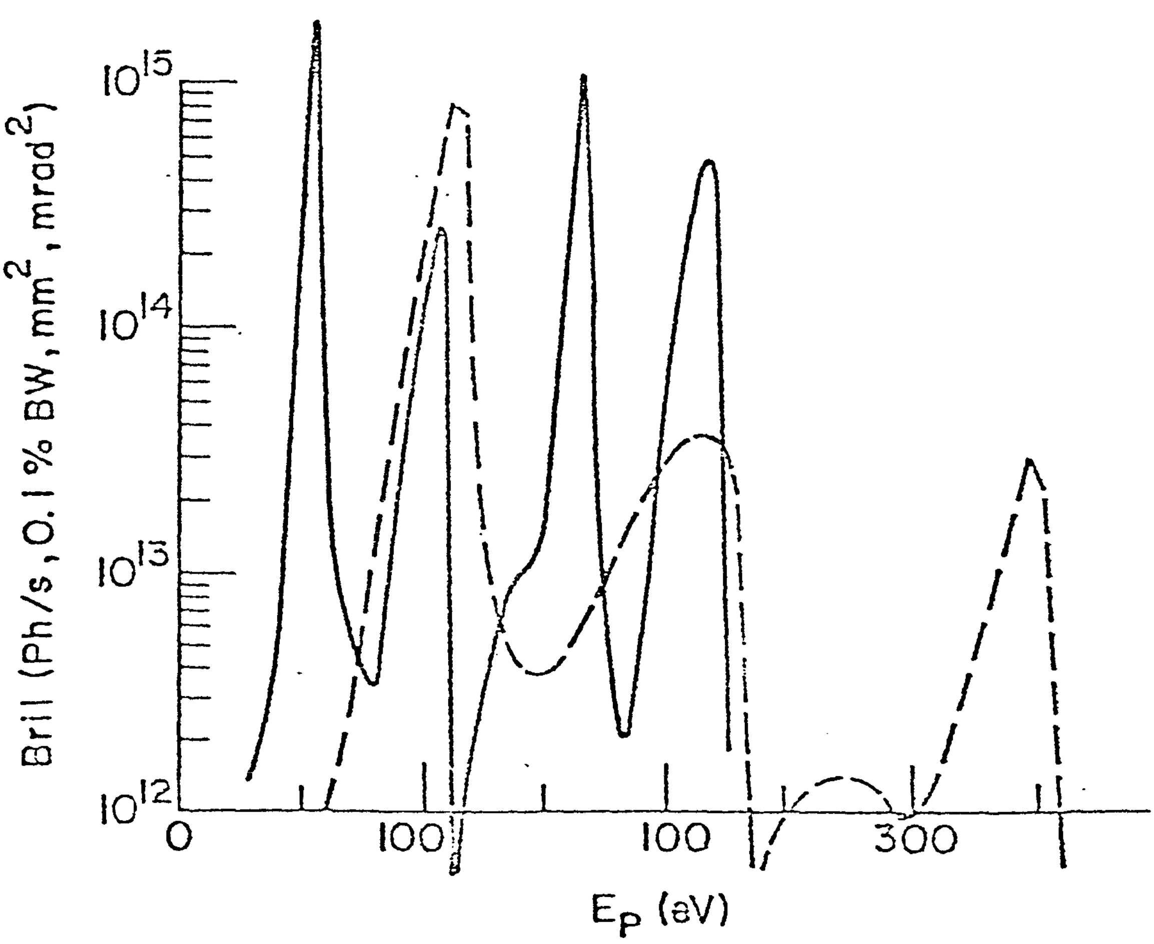
8.	W. T. Capehart	General Motors
9.	C. Segre	Illinois Institute of Technology
10.	D. W. Lynch	Iowa State University
11.	Z. D. Hurych	Northern Illinois University
12.	A. Sooryakumar	Ohio State University
13.	F. C. Brown	University of Illinois
14.	J. H. Weaver	University of Minnesota



CLAMSHELL OPEN (ZERO FLUX)
GAP @ λ_0 = 7 cm
G = OO
G = 6.6 cm
G = 5.1 cm
G = 4.2 cm
G = 3.5 cm
GAP = 3.5 cm
(CLAMSHELL CLOSED)
K=0
K=0.5
K=1.0
K=1.5
K=2.0
K=2.5
E_p (eV)
200
100
0
4
6
8
10
λ_0 (cm)

Fig-1



10^{15}
10^{14}
10^{13}
10^{12}
Bril (Ph/s, 0.1 % BW, mm^2, mrad^2)
0
100
100
300
E_P (eV)

Fig-2

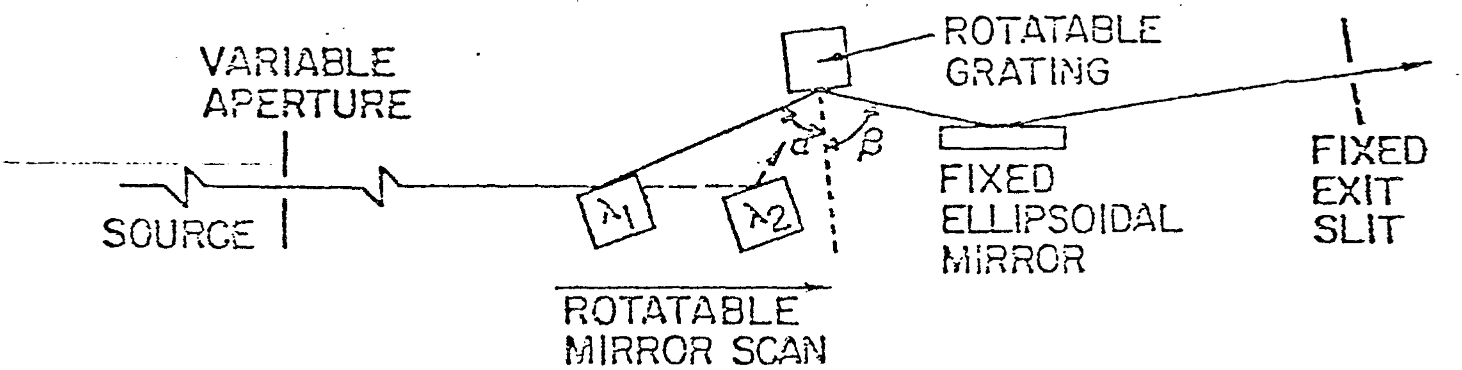

VARIABLE
APERTURE
SOURCE
ROTATABLE
GRATING
λ1
λ2
α
β
FIXED
ELLIPSOIDAL
MIRROR
FIXED
EXIT
SLIT
ROTATABLE
MIRROR SCAN

Fig. 3